Hot-Dip Galvanized Steel Bridges:

a practical design guide

content

Introduction

Whether arching over a rushing river or connecting interstate and highway systems, bridges are an everyday part of our nation's transportation system. These critical elements knit together communities across the country, providing safe travel of goods and people. Constructing new bridges is a complex, expensive, and time-consuming endeavor; and thus, it is paramount to design effective, sustainable bridges for today as well as future generations.

In 2013, the American Society of Civil Engineers (ASCE) rated the US bridge infrastructure a C+, as one in nine of the nation's bridges are rated as structurally deficient, and the average bridge age is 42 years. Technology, design innovation, and materials, as well as the type and volume of vehicles have evolved significantly in this time-frame, and maintaining or retrofitting these existing structures is both costly and labor intensive. As new and replacement bridges are built, the Federal Highway Administration (FHWA), state/province Departments of Transportation (DOTs/MOTs), and local governments are looking to the future.

Planning for the future, or building 100-year bridges, is a nod to sustainable development. If environmentally-friendly, economically-feasible bridges are constructed today, future generations will inherit a better infrastructure system than current conditions. To build sustainable bridges, it is imperative to evaluate the construction materials used to ensure they can not only meet the long design life without significant deterioration, but also without unnecessary cost.

Hot-dip galvanized steel has been used in bridge designs for generations. The economical, long-lasting protection system affords bridge designers the life and minimal maintenance they desire. As with any building material, there are certain best practices for design and service environments that ensure the highest quality, longest lasting galvanized steel bridges. Understanding both the benefits and limitations of galvanized steel will assist bridge engineers in evaluating if hot-dip galvanizing is a solution for their bridge project.

Hot-Dip Galvanizing

Hot-dip galvanizing (HDG) is the process of dipping fabricated steel into a kettle or bath of molten zinc (*Figure 1*). While the steel is in the kettle, the iron in the steel metallurgically reacts with the molten zinc to form a tightly-bonded alloy coating that provides corrosion protection. The process is inherently simple, and consists of three basic steps:

1. **surface preparation**: a process of three steps the steel goes through before galvanizing including degreasing/caustic cleaning, pickling, and fluxing
2. **galvanizing:** the actual dipping of the steel into a bath of ≥ 98% pure zinc
3. **inspection:** verifying the galvanized coating meets ASTM standards

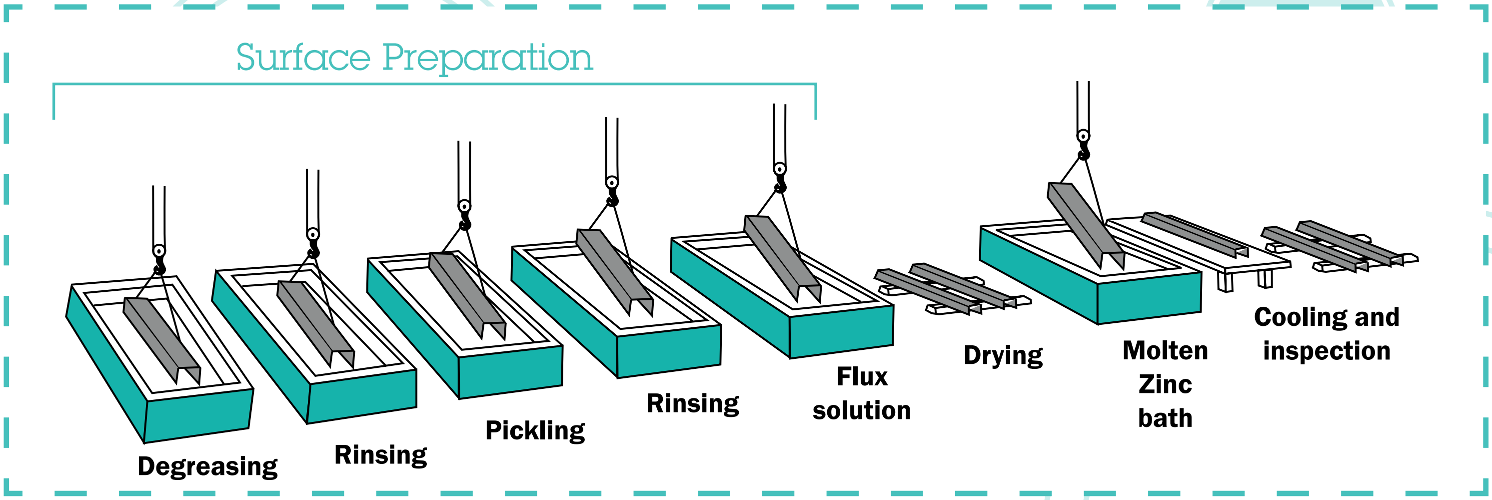


Figure 1: Hot-Dip Galvanizing Process

Surface Preparation

Surface preparation is critical to hot-dip galvanizing, as the zinc will not react with unclean steel surfaces. Any failures or inadequacies in surface preparation are immediately apparent when the steel is withdrawn from the zinc bath, as the unclean surfaces will not be coated. Surface preparation for galvanizing is done with chemical cleaning and contains three steps:

Degreasing/Caustic Cleaning – A hot alkali solution, mild acidic bath, or biological cleaning bath removes organic contaminants such as dirt, paint markings, grease, and oil from the steel surface. Epoxies, vinyls, asphalt, or welding slag, which cannot be removed by this cleaning solution, must be removed by grit-blasting, sand-blasting or other mechanical cleaning.

Pickling – After the degreasing, the steel is rinsed and then dipped into the pickle bath, a diluted solution of heated sulfuric acid or ambient hydrochloric acid. Pickling removes mill scale and iron oxides (rust) from the surface, leaving the steel in a state of white metal clean. As an alternative or in conjunction with pickling, you can abrasive clean the steel.

Fluxing – Following another water rinse, the steel moves to the final stage of surface preparation: fluxing. The flux is a zinc chloride ammonium chloride solution that serves two purposes - removes any remaining oxides and leaves a protective layer on the surface to prevent iron oxide from forming prior to galvanizing.

Galvanizing

After surface preparation, the steel is completely immersed in the zinc bath. The bath consists of ≥ 98% pure zinc heated at 815-850 F (435-455 C). While the steel is in the zinc bath, a metallurgical, diffusion reaction occurs to develop a series of zinc-iron intermetallic layers. The coating grows perpendicular to all steel surfaces, ensuring complete, uniform coverage of all corners and edges, as well as the inside of hollow structures. After the coating growth is complete, the steel is withdrawn from the kettle allowing excess zinc to drain off the part.

Inspection

Once the galvanizing step is complete, the steel is inspected to ensure conformance to ASTM specifications. The two properties of the hot-dip galvanized coating most closely scrutinized are coating thickness and appearance/surface condition. The appearance is observed by the naked eye, and coating thickness is measured by magnetic thickness gauges.

More information on testing methods and interpretation can be found in the American Galvanizers Association (AGA) publication *Inspection of Hot-Dip Galvanized Steel Products* as well as the AGA's inspection app, available for download at no cost in the Apple and Google Play stores.

Hot-dip galvanizing has been specified to combat steel corrosion for more than 100 years; however, the specification and use of galvanized steel evolves constantly as new markets emerge. Though corrosion resistance is inherent any time hot-dip galvanizing is utilized, there are a number of other benefits including low initial and life-cycle costs, durability, longevity, availability, versatility, sustainability, and aesthetics that lead to the specification of galvanized steel. For more information on these benefits, download the AGA's publication, *Hot-Dip Galvanizing for Corrosion Protection: A Specifier's Guide.*

Designing Galvanized Steel Bridges

The key to designing successful hot-dip galvanized steel bridges begins at the drawing board. Communication between the design engineer, fabricator, and galvanizer early in the design process can alleviate potential pitfalls. There are certain design and fabrication details that will produce better quality galvanized coatings, help reduce costs, and improve turnaround times. There are a handful of ASTM specifications developed to facilitate the design of products for hot-dip galvanizing which are also explained in detail in the AGA's design guide, *The Design of Products to be Hot-Dip Galvanized after Fabrication.*

Bridge engineering requires exact calculations and testing to ensure the overall integrity of the bridge. The information in the *Design Guide* is a great starting point, but there are a few additional considerations that should be factored into the bridge design when planning to galvanize. The hot-dip galvanizing process does not change the mechanical properties of the steel, but because the process requires the parts to be heated and cooled, it can induce or relieve stresses in the steel. Furthermore, the thickness and weight of the bridge parts will be slightly different after galvanizing because of the addition of the zinc coating. This can be particularly important in respect to connections and fasteners. The next sections in the publication will provide more information about specific, common areas of concern when designing galvanized steel bridges. These are good topics to discuss with the galvanizer early in the process, and include:

1. Size Limitations
2. Girder Design
3. Dissimilar Metals
4. Steel Selection
5. Coating Thickness

Size Limitations

As the size, number, and weight of vehicles on the road continues to grow, bridge designs have expanded to accommodate this traffic. Hot-dip galvanizing is a complete immersion process, which means the parts must fit in the zinc bath to be coated. In North America, the average kettle length is 40 feet (although there are many 50-65 foot kettles), with depths ranging from 6-12 feet, and widths of 5-11 feet. Although there are size constraints based on the size of the zinc bath, there are a few options to galvanize larger spans.

Modular Design

The easiest way to galvanize larger spans is to design the bridge in modules or sub-units to fit in the galvanizing kettle. Designing the pieces to fit in the galvanizing bath in one pass eliminates the challenges of progressive dipping, reduces the potential for warpage, and provides additional savings in manufacturing and assembly because of simplified handling and transportation. The sub-units can be connected after galvanizing by field-welding or bolting. A great example of a bridge utilizing galvanized sub-units is the Stearns Bayou Bridge (left).

Modular design can also provide advantages when accelerated bridge design is desired. One innovative design, developed and tested by the Bridge Technology Center within the Short Span Steel Bridge Alliance (SSSBA), is the press-brake-formed tub girder (or folded plate). This modular design allows a galvanized tub to be precast with a deck and shipped to the site to lay in place. The first short span bridge utilizing this technology, the Amish Sawmill Bridge, was opened in Fairbank, Iowa, in January 2016. For more information, visit shortspansteelbridges.org.

Modular Design Case Study: The Steans Bayou Bridge

The Stearns Bayou Bridge, installed in 1966, is believed to be the first fully galvanized bridge in the United States. The bridge is 420 feet long, consisting of two 60-foot and six 50-foot spans, a 30 foot roadway, and five foot walkway on each side. In addition to the beams, all diaphragms, bearing pads, handrail, and shear connectors were also hot-dip galvanized. An inspection in 1997 revealed the galvanized steel to still be in good condition with mild staining and no visible rust. Coating thickness measurements were taken on the bridge, and were as follows:

Sample Area	Coating Thickness (Mils)	Projected Time to First Maintenance
Beams/Diaphragms	6.3	>95 Years
Bearing Pads	2.9	95 Years
Handrails	1.9-4.6	65-95 Years

In the rural environment, even with the harsh winters in Michigan, which lead to salt, standing water, and snow pile up on the galvanized steel, the bridge was projected to last at least another 65 years in 1997, which would be 2062, essentially giving the Stearns Bayou Bridge a minimum 100-year life.

Progressive Dipping

If modular units aren't possible or still too large, the dimensions of the kettle are not the actual maximum size of pieces that can be galvanized, as pieces can be progressively dipped. Progressive dipping is simply the process of coating the steel part in two passes. In other words, if half of the piece can fit in the bath, the part can be galvanized on one side, rehung, and then dipped on the remaining surface. In essence, this would nearly double the size of part that can be coated.

There are some unique challenges when it comes to progressive dipping, and it is crucial to have communication with the galvanizer early in the design phase to minimize these concerns. When steel is heated it expands, and as it cools it contracts; therefore, when part of a steel article is heated and the other part is cool, there is an increased risk for distortion. The galvanizer will be able to provide recommendations to minimize this concern, as well as verify any weight or building constraints to processing the piece at their specific facility. Progressively dipped pieces often have an overlap area that is visible on the piece. The line or darker area is purely cosmetic, and will fade over time as the coating weathers naturally. However, the overlap area will most likely have a thicker coating, so it is important to consider this if the area will be an important connection point with other pieces.

Complementary Coating: Metallizing & HDG

Hot-dip galvanizing and zinc spray (metallizing) can be used in tandem on large or complex structures. Zinc spraying, or metallizing, is accomplished by feeding zinc wire or powder into a heated gun where it is melted and sprayed onto the part using combustion gases and/or auxiliary compressed air. The 100% zinc coating can be applied in the shop or the field to any size part, and is often sealed with a low viscosity polyurethane, epoxy-phenolic, epoxy, or vinyl resin. Because both coatings are comprised of zinc, there is no concern for galvanic corrosion present when dissimilar metals are connected.

Because metallizing requires specialized equipment and a skilled operator, it is expensive initially. Hot-dip galvanizing smaller parts of the bridge, or dipping the ends of larger pieces and metallizing the center are common practices as galvanizing provides economic efficiencies. Furthermore, the two coatings have similar appearances both initially and as they weather, providing the bridge with a cohesive look. Finally, if the metallized coating is applied properly and thick enough, the corrosion performance will be similar to hot-dip galvanized steel. The Castleton Bridge in Indiana (left) is a great example of a bridge currently using both hot-dip galvanized and metallized steel.

Complimentary Coating Case Study: Castleton Bridge

The Castleton Bridge, constructed in 1970 in Indiana, demonstrates the use of hot-dip galvanizing and metallizing together in a unique way. Typically, the two coatings are used on the same piece, in a planned, purposeful way, such as to cover the middle of a beam that is too large to be fully galvanized, even when using progressive dipping.

When the Castleton Bridge was built, the southbound side was painted and the northbound side was galvanized, for research purposes. After 14 years, the painted side required repainting, while the galvanized side remained untouched. Then, in 2002, the painted side was in need of repair again. This time the Indiana DOT elected to metallize the girders, based on the performance of the hot-dip galvanized southbound sections.

In 2011, the metallized and galvanized girders were both inspected and continue to perform well. The hot-dip galvanized girders have not required maintenance throughout the 41 years of service, and still have enough zinc present to meet the minimum coating thickness requirements in ASTM A123. Similarly, since metallizing in 2002, the northbound bridge has not required any additional maintenance.

Girder Design

The unique web and flange steel thickness in modern girder design, coupled with welding 75–100-foot (23–31 meter) weld lengths, can create specific challenges associated with galvanizing that must be considered by the design team in order for the highest quality galvanized girder to be delivered to the job site. (See *Effective Girder Design*, right.)

Effective Girder Design

1. The flange-to-web thickness ratio should be no more than 3 to 1 to avoid distortion of the web.
2. The finished galvanized girder should be air cooled and not water quenched to minimize the induced stress from the cooling cycle.
3. Continuous welding should be used to prevent weld fracture from large forces generated when stress relieving the steel at the galvanizing temperature, or from trapped pre-treatment liquids expanding at the galvanizing temperature.
4. Hot-dip galvanizing may accentuate or remove a camber. This is not usually problematic as the diaphragm members attached during construction can be used to draw the girder in to place. This is done by welding or fastening (with hot-dip galvanized connections) the diaphragm steel members to the girder, starting at one end of the girder and working to the other end.
5. Stiffeners should be used and they should be liberally cropped (1” [2.5 cm] or greater) to allow for the free flow of cleaning solutions and molten zinc within the web space.
6. Steel should not be left in the molten zinc bath longer than necessary. A longer immersion time applies more heat than necessary to the steel and can result in relieving more stresses which may manifest as warpage/distortion.
7. Any lifting (material handling) of the girder should be at the quarter points to avoid permanent deflection caused by the self-weight of the product.
8. To completely support a positive or negative camber and avoid flattening, lay the newly galvanized girder on the strong axis and support with as many blocks as possible.

Dissimilar Metals

Where zinc comes into contact with another metal, the potential for corrosion through a bi-metallic couple exists. The creation of a bi-metallic couple will lead to accelerated corrosion of the anodic metal. The extent of the accelerated corrosion is dependent on the positions of the metals in the *Galvanic Series of Metals*, as well as the relative size of the surface area of the two metals in contact.

Zinc, which comprises the hot-dip galvanized coating is very high in the *Galvanic Series of Metals* (*Figure 2*), which means it will be anodic to most other metals. So, when hot-dip galvanizing is connected to other metals, the zinc coating will not only sacrifice itself to protect the underlying base steel, but also try to protect the other connected metals. This will lead to a more rapid consumption of the zinc coating, and decrease the overall life.

When it comes to bridge design, the most common metals that may come in contact with the steel are likely painted (bare) steel, weathering steel, and stainless steel. It would not be recommended to connect bare steel to galvanized steel, as the zinc will want to protect all of the carbon steel and the overall coating performance life will be decreased. However, if the other steel surfaces are painted or isolated with a non-conductive material, these connections will not significantly decrease the life of the galvanized coating as

CORRODED END
(Anodic or less Noble)
Magnesium
Zinc
Aluminum
Steel
Lead
Tin
Nickel
Brass
Bronzes
Copper
Stainless Steel (passive)
Silver
Gold
Platinum
PROTECTED END
(Cathodic or more Noble)

Figure 2: Galvanic Series of Metals

long as the paint or isolating materials are maintained over the coating lifetime.

When connecting galvanized steel pieces to stainless or weathering steel, there are other considerations. Under atmospheric conditions of moderate to mild humidity, contact between a galvanized surface and a stainless steel surface is unlikely to cause substantial corrosion. However, if the metal surfaces are in the presence of salt water or marine air, it would be best to electrically isolate the two metals.

When connecting hot-dip galvanized steel to weathering steel, for instance using galvanized bolts on weathering steel beams, the zinc will initially sacrifice itself to protect the weathering material until the protective layer of rust patina develops. Once the rust patina is in place, it will prevent further sacrificial action from the zinc. So, when connecting the two metals, it is important to ensure the galvanized coating is thick enough to last until the rust patina forms usually a few years. Most hot-dip galvanized bolts will naturally have enough coating to withstand the years of rust patina development with only a minimal loss in coating life.

Steel Selection

Steel composition has a profound effect on the characteristics of the galvanized coating. Selecting steels with recommended chemistries for hot-dip galvanizing is important to help control the coating thickness and appearance. The two trace elements that are most important, as they act as catalysts to the galvanized coating growth, are silicon and phosphorous. There are a few guidelines in steel selection to try to control the level of these trace elements and others to provide typical galvanized coatings:

- Levels of carbon less than 0.25%, phosphorus less than 0.04%, or manganese less than 1.35% are beneficial
- Silicon levels less than 0.04% or between 0.15%-0.22% are desirable (*Figure 3*) (Silicon may be present in many steels commonly galvanized even though it is not a part of the steel's controlled composition, because silicon is used in the steel deoxidation process and is found in continuously cast steel.)

Steels with the recommended ranges of silicon and phosphorus will develop typical zinc-iron alloy layers that represent 50-70% of the total coating thickness, with an outer layer of free zinc comprising the rest. However, even when both elements are individually held to desirable limits, the combined effect between them can still produce an atypical coating.

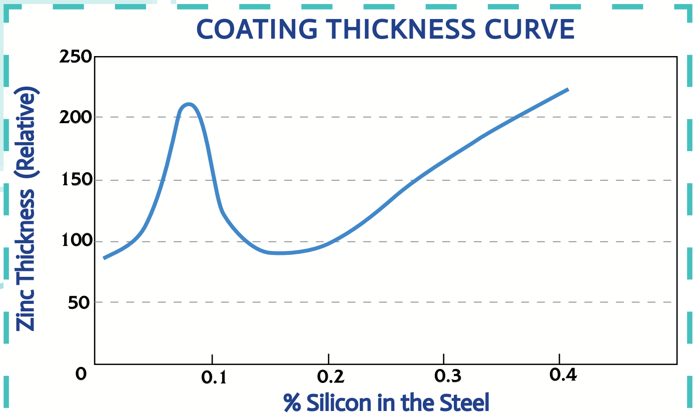


Figure 3: Effect of Silicon on Coating Thickness

Atypical galvanized coatings produced from reactive steels may produce coatings comprised entirely or almost entirely of zinc-iron alloy layers (*Figure 4*). These tend to be thicker coatings that can affect both the appearance and adherence of the zinc coating. Because of the increased thickness, atypical coatings tend to have an initial matte gray appearance and a rougher surface than typical galvanized coatings. If the highly reactive steel leads to an excessively thick coating (beyond 8-10 mils) adhesion concerns such as flaking and delamination can occur, particularly under external stress.

Reactive steel is still galvanized on a regular basis, and it is important to note the difference in appearance has no effect on the corrosion protection afforded by the zinc. Communication between fabricator and galvanizer can minimize reactive steel effects.

Figure 4: Recommended Silicon (left) vs Reactive Steel (right) (not to scale)

Coating Thickness

In order for the metallurgical reaction between the iron and zinc to occur, the steel must be heated to the bath temperature. Because certain bridge elements, such as girders, are often large, heavy structures, they are more susceptible to producing thicker coatings. First of all, the larger pieces will be in the bath and/or near bath temperature for longer periods, which can lead to more coating growth. Second, the most common steel bridge specifications have maximum silicon ranges at 0.40%, so it is possible to have highly reactive steels to start with. Finally, as mentioned before, progressively dipped pieces are likely to have thicker coatings in the overlapped area. It is also important to consider the chemistry of weld rod material when welding before galvanizing, because the silicon content of the weld material can affect the coating growth in that area.

Case Study: Coating Thickness Increased in Weld Area

This is common and occurs when the selected weld rod material is more reactive than the surrounding steel. High silicon levels in the rod lead to increased thickness, also commonly called a bloated or swollen weld, which is often duller in appearance, rougher, and thicker. The problem can be avoided if the fabricator selects weld rod materials that are compatible with the silicon level of the steel being welded. The increased zinc thickness in the weld area is acceptable because it does not affect the corrosion performance of the galvanized coating. It is only cause for rejection if it interferes with the intended use of the part, such as for handrails. If required, it is possible to grind down the thick coating in the weld areas to make the handrail smooth. Stripping and regalvanizing the part is met with limited success – often the problem just reappears after the second coating, because the silicon levels are still present.

Overtapping Guidelines for Threaded Assemblies

Typical coating thickness on bolts can range from 1.8 to 3.5 mils (0.045 to 0.09 mm), which can make standard bolt and nut tolerances difficult to maintain for correct assembly. If bolts are hot-dip galvanized, then the nuts should be oversized to accommodate the 3.6 to 7.0 mils (0.09 to 0.18 mm) increase in bolt diameter after galvanizing (oversize tolerances are detailed in ASTM A563, *Standard Specification for Carbon and Alloy Steel Nuts*).

If the nuts or tapped holes in a steel article are hot-dip galvanized, they should be re-tapped or re-threaded after galvanizing to remove the zinc coating and provide clearance for the coated bolt. When the fastener system is assembled, the coating from the bolt will provide protection for the uncoated nut thread since zinc coatings cathodically protect uncoated steel. The re-tapping is done on the nut side so that no uncoated threads on the bolts will be available to weather without galvanized protection. If re-tapping the nuts, it's important to note all of the zinc coating must be removed from the inner threads.

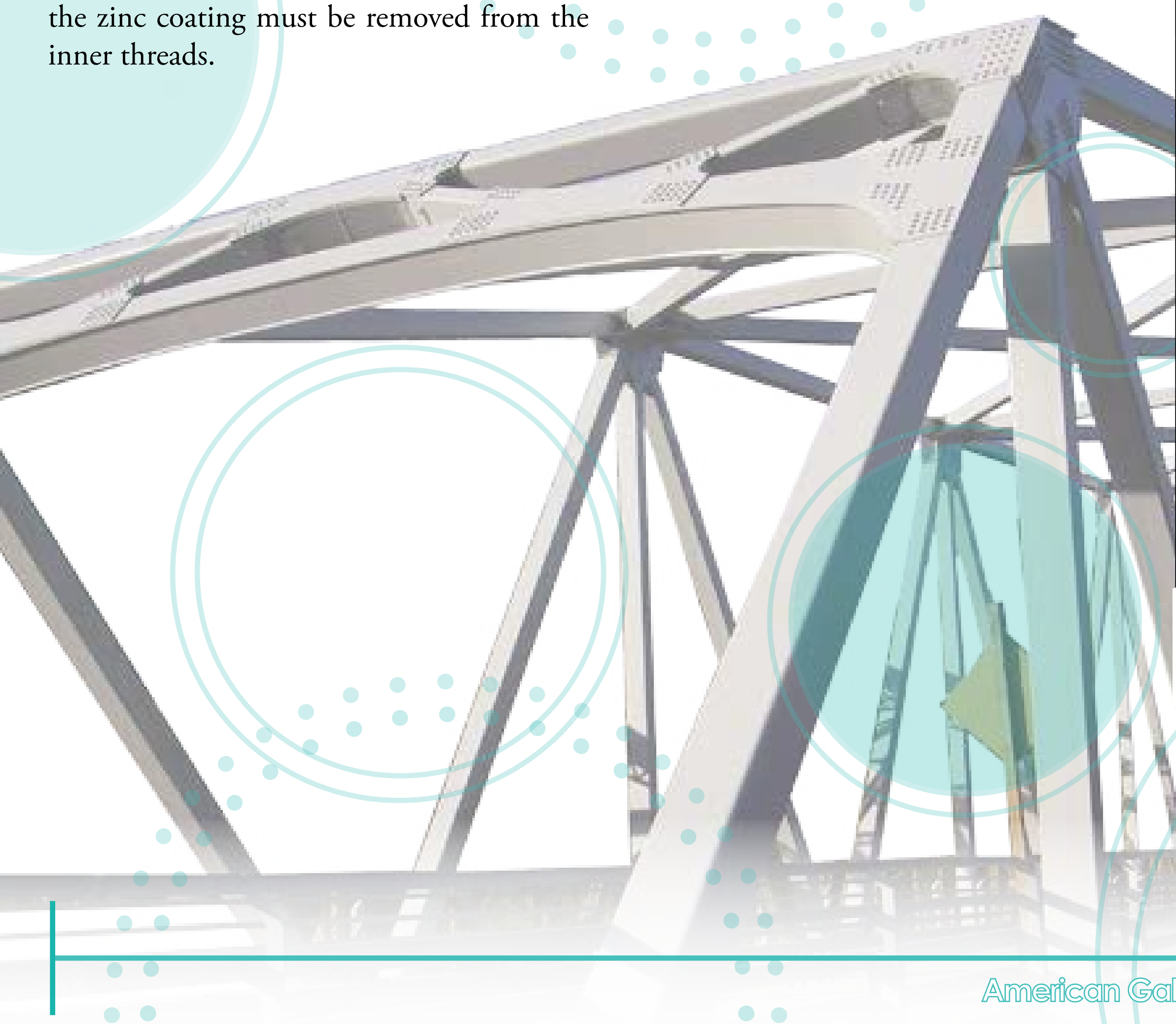
Standard practice for structural connections is to galvanize the nuts as blanks and then to tap the threads after galvanizing. Although bare, nut threads will be protected by the zinc on the coated threads of the bolt.

Table 1 shows the recommended overtapping for nuts and interior threads as detailed in ASTM A563, *Specification for Carbon and Alloy Steel Nuts*. On threads over 1.5 inches (38 mm) it is often more practical, if design strength allows, to have the male thread cut 0.031inch (0.8 mm) undersize before galvanizing so a standard tap can be used on the nut. For metric overtapping allowances, see ASTM A563M, Section 7.

Clearance holes for structural connections may also require oversizing. As a result, this may necessitate unblocking or cleaning of the hole after galvanizing. For slip critical connections, add 1/16 inch to the standard clearance hole size for any size bolt. This will give a clearance hole that can accommodate the increased diameter of a galvanized bolt without need of extra hole cleaning.

Nominal Nut Size (in) & Pitch	Diametral Allowances (in)
0.250-20	0.016
0.312-18	0.017
0.375-16	0.017
0.437-14	0.018
0.500-13	0.018
0.562-12	0.020
0.625-11	0.020
0.750-10	0.020
0.875-9	0.022
1.000-8	0.024
1.125-8	0.024
1.125-7	0.024
1.250-8	0.024
1.250-7	0.024
1.375-8	0.027
1.375-6	0.027
1.500-8	0.027
1.500-6	0.027
1.750-5	0.050
2.000-4.5	0.050
2.250-4.5	0.050
2.500-4	0.050
2.750-4	0.050
3.000-4	0.050
3.250-4	0.050
3.500-4	0.050
3.750-4	0.050
4.000-4	0.050

Table 1: Threaded dimensions and overtapping allowances for nuts



Minimizing Warpage & Distortion

Some fabricated structures and assemblies may distort at the galvanizing temperature as a result of relieving stresses induced during steel production and in subsequent fabricating operations. In general, the potential for warpage/distortion can be greatly reduced through design and production engineering measures to avoid high internal stresses. Starting discussions between the designer, fabricator, and galvanizer early in the design process is good practice to ensure alternative design features can be incorporated to prevent issues.

The guidelines for minimizing distortion and warpage are provided in ASTM A384, *Safeguarding Against Warpage and Distortion During Hot-Dip Galvanizing of Steel Assemblies.* The following design practices and fabrication techniques are known to increase the susceptibility for warpage and distortion and should therefore be minimized or eliminated in bridge design wherever possible.

Steel should not be left in the molten zinc bath longer than necessary. A longer immersion time builds heat in the steel that must be released as the part cools to ambient temperature and can cause increased stress between parts in the assembly.

Avoid Susceptible Thin Sheet Steels

Steel invariably contains internal stresses induced at the mill from rolling operations used to bring structures, plate, and sheet to the final thickness. The most commonly distorted members of assemblies are that of sheet or plate which is ¼ inch in thickness or less – the lighter the gauge of the steel, the greater the risk of warpage or distortion. Oftentimes sheet or plate can be returned to a flattened state using a jig or by weighing the product down on a flat surface during the cool-down.

Thin sheets that warped during the galvanizing process

Minimize Internal Stresses Induced By Cold Working

To reduce or eliminate the potential for warpage/distortion due to cold working, bending should be performed at the largest acceptable radii to minimize local stress concentration and the design should be optimized to reduce punched holes, rolling, riveting, bending, and straightening (*Figure 5*). After galvanizing, these products should be air cooled (instead of quenched) to minimize induced stress from the cooling cycle. Where excessive cold working or tight bend radii cannot be avoided, the product should be stress relieved per the guidelines provided within ASTM A143, Section 6.

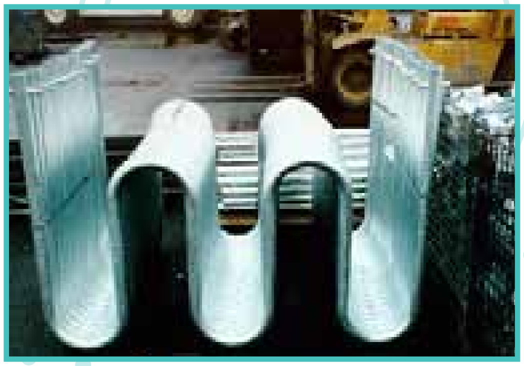


Figure 5: Excessive cold working can result in strain-age embrittlement

Developing a Welding Sequence Plan

A welding sequence plan should be carefully developed and adhered to during fabrication to ensure welding stresses are distributed equally over the entire cross-section of the assembly and therefore minimize the potential for warpage/distortion. The following guidelines should be used to develop a welding sequence plan:

- Weld the assembly from inside to outside to avoid high shrinking stresses.
- Avoid the need to force, spring, or restrain components during welding.
- Avoid over-welding and use as few weld passes as possible.
- Continuously weld thick sections, however, thin sections may benefit from staggered welding. For staggered welding of 1/8" or lighter material, weld centers should be closer than 4".

Optimize Welding Before Hot-Dip Galvanizing

Figure 6: Additional welding performed on assembly's right side resulted in an uneven distribution of weld stresses, causing distortion of the internal plate.

Welding results in significant residual stress in small areas of an assembly due to the extreme temperature differences experienced. All efforts should be made to keep the stresses in the construction as low as possible right from the beginning to enable the steel to absorb the internal stresses completely. The overall amount of welding can be minimized by using bolted connections or performing assembly after hot-dip galvanizing. Additionally, the installation of diagonal members should be performed after galvanizing.

Where welding before galvanizing cannot be avoided, the internal stresses in the connections can be minimized by avoiding joint designs or weld lengths which are greater than statically required, and by placing welds near to and symmetrically around the neutral axis - aligning welds so that shrinkage and opposing forces are balanced rather than all pulling in the same direction.

Avoid Asymmetrical Design

Symmetrical sections such as I-beams and tubing will be less likely to distort than asymmetrical pieces (camber beams, channels, tees, custom beams, girders) because the thermal expansion forces above and below the natural axes balance each other. Furthermore, cylindrical structures are less likely to warp or distort than rectangular or elliptical ones. Conversely, the internal stresses in asymmetrical designs (*Figure 7*) will be relieved unevenly due to the constraints

Figure 7: Asymmetrical fabrications are susceptible to warpage

of the material's shape. Specify symmetrically rolled sections instead of angle or channel frames. Refer to *figures 7-12* for various methods to reduce or eliminate the potential for warpage and distortion.

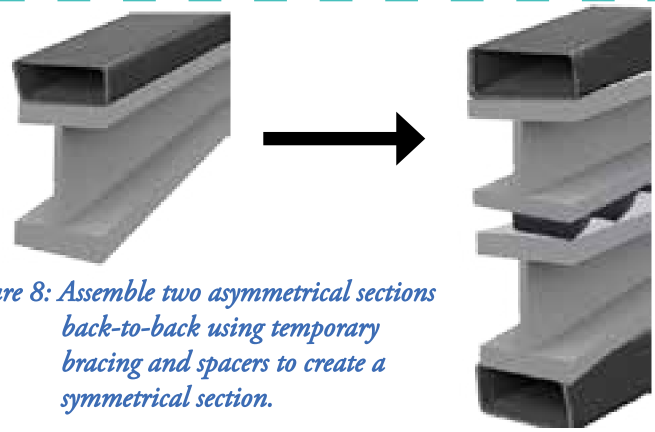


Figure 8: Assemble two asymmetrical sections back-to-back using temporary bracing and spacers to create a symmetrical section.

Figure 9: Fabricate and galvanize individual part as separate loose items and then assemble after galvanizing.

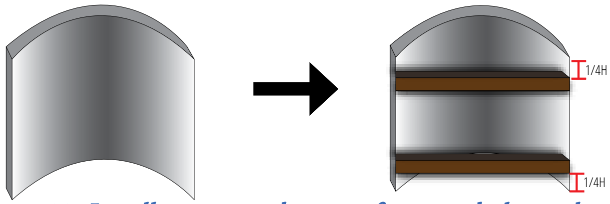


Figure 10: Install temporary bracings for curved plates, channel frames, and troughs which are proportional to plate thickness and located at quarter points of the product height. Bracing design should always be discussed with the galvanizer in advance.

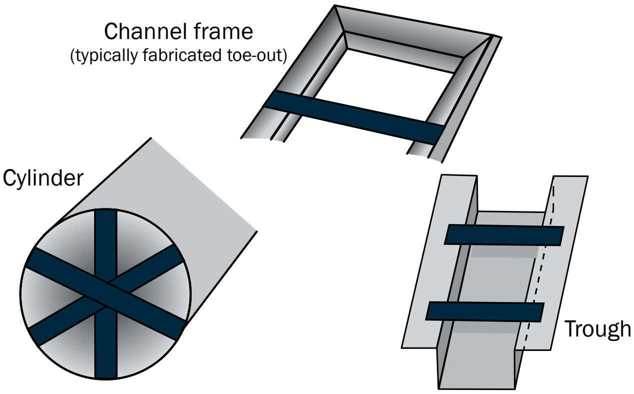


Figure 11: Example of temporary bracing designs for channels, cylinders, and troughs.

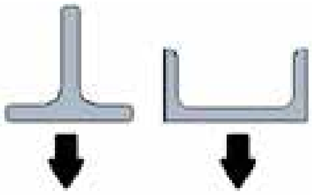


Figure 12: Dip tees flange-side first and channels web-side first. Perform immersion as quick as possible and at the largest possible dip angle. Air cool to minimize the induced stress from the cooling cycle.

Minimize Thick and Thin Material in the Same Assembly

When two steels of different thicknesses are assembled and brought up to galvanizing temperature, the thinner steel heats up and expands more quickly than the thicker steel. If the thicker steel restrains the thinner steel from expanding freely, warpage/distortion of the thinner steel can occur. Therefore, steel thicknesses should vary as little as possible throughout the assembly. Uneven thickness at joints should be avoided (*Figure 13)* along with the surrounding of thinner material with thick framing (*Figure 14*), unsupported flast sheet assemblies (*Figure 15*), and flange-to-web thickness ratios greater than 3 to 1 for fabricated beams (*Figure 16*). Wherever possible, galvanize thick and thin portions separately and join them after galvanizing.

Figure 13: Avoid uneven thickness at joints

Case Study: Warpage Due to Asymmetrical Design

The design of the part above includes a top flange from channel material, but has no corresponding bottom flange to make the design symmetric. This allows the buildup of stress during the thermal expansion of the part in the galvanizing kettle to be relieved by distorting the entire piece from one end to the other, following the most likely rolling direction of the steel used for the web portion of this part.

This figure below shows a fabrication where a plate was welded to the side of a beam. When this fabrication was brought up to galvanizing temperature, the thermal expansion proceeded at different rates for the beam and the plate. This put considerable stress on the plate as it tried to expand more rapidly than the beam, however, the welding together of the two materials did not allow for separate movement. Since the plate material cannot move near the weld joint, it relieved the stress build-up by distorting away from the weld joint and cracking the weld joint.

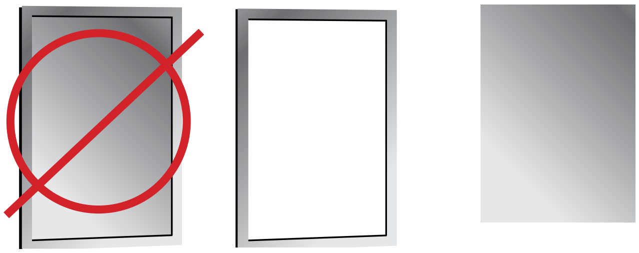


Figure 14: Avoid galvanizing frames containing thinner plates. These parts should be galvanized separately and assembled after galvanizing to minimize the potential for plate warpage and weld cracking galvanizing.

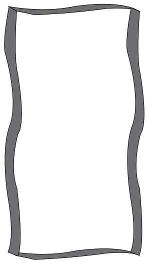


Figure 15: Warpage of structures with unsupported flat sheets can be greatly minimized by the addition of stiffeners.

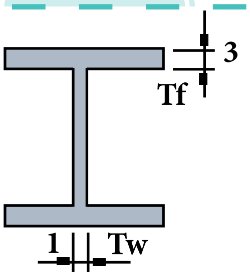


Figure 16: Flange-to-web thickness of fabricated beams (Tf to Tw) should be no more than 3 to 1.

Ensure Best Practices For Laydown After Galvanizing

If a hot-dip galvanized product is laid down haphazardly after removal from the galvanizing kettle, or onto supports which are too far apart, the product can sag under its own weight and permanently retain a bowed shape after cooling (*Figure 17*). To reduce or eliminate the potential for warpage/distortion due to poor laydown techniques, arrange products flat and free from external forces during the cool-down phase, and use additional supports underneath the mid-section of products to prevent sagging (*Figure 18*). To support a positive or negative camber, lay the product on the strong axis and support with as many blocks as possible (*Figure 19*).

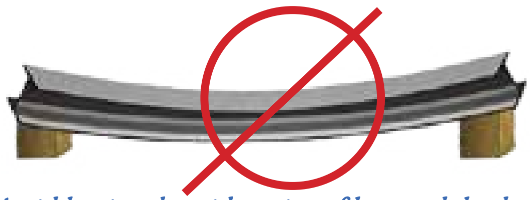


Figure 17: Avoid leaving the mid portion of long and slender products unsupported as sagging can introduce a permanent bow.

Figure 18: Products should be laid flat after galvanizing. Additional supports should be added along mid-sections as required to prevent sagging.

Figure 19: To support a camber beam, lay the product on the strong axis and support with as many blocks as possible.

Account for Thermal Expansion When Progressive Dipping

It is preferable to build assemblies in suitable modules so they can be immersed quickly and galvanized in a single dip to ensure uniform expansion and contraction. When progressive dipping is required, the risk of distortion can be reduced by consulting with the galvanizer to take into account length variations of the assembly and planning for thermal expansion conditions.

Optimize Drainage, Venting, & Lifting for Long/Slender Products

When a long and/or slender product is lifted at both ends throughout the galvanizing process, deflection caused by the self-weight of the product (*Figure 20*) or by the weight of zinc unable to properly drain from the structure (*Figure 21*) can occur. To reduce or eliminate the potential for a bowed product, the lift points for galvanizing should be located at quarter points along the product length, venting and drainage holes should be designed per ASTM A385, and drainage should be maximized at the ends of hollow sections (*Figure 22*).

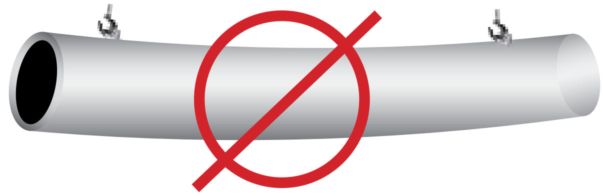


Figure 20: Avoid lift points at the ends of long or slender products which result in bowing or sagging

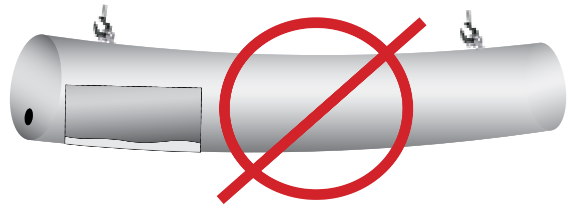
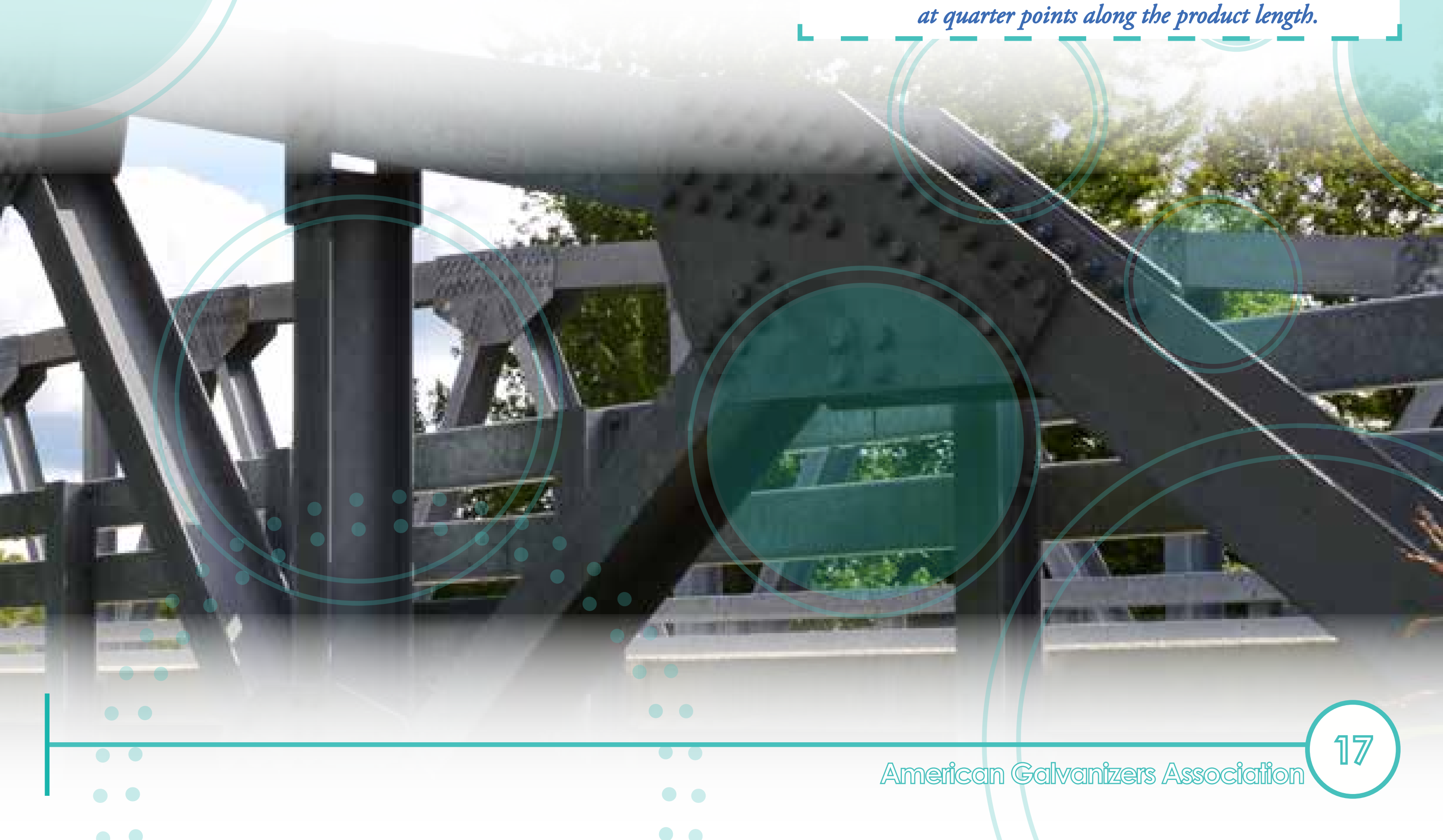


Figure 21: Optimize venting & drainage design per ASTM A385 to avoid permanent bowing the article due to entrapped zinc weight

Figure 22: Lift points for galvanizing should be located at quarter points along the product length.



Connection Concerns

Utilizing hot-dip galvanized fasteners for both bearing and friction type connections is a very effective way to provide corrosion protection. In addition to overtapping/oversizing to allow for the zinc coating thickness, there are additional considerations when specifying bolted hot-dip galvanized structural joints for steel bridge design. By taking into account oversizing allowances, tensioning, and slip coefficients as they relate to hot-dip galvanized connections, it is possible to ultimately save time and money down the road by simplifying bridge design and installation.

Bearing Type Connections

The presence of protective zinc coatings on the contact surfaces of bearing type connections is not detrimental to their performance. Galvanized joints of this type have a long and outstanding performance history in multiple industries. If hot-dip galvanized fasteners are to be used in a bearing type connection design, the clearance holes must be designed to the standard clearance hole diameter. This may necessitate unblocking or cleaning of the hole after galvanizing, but the American Institute of Steel Construction (AISC) guidelines in the AISC Manual of Steel Construction: *Load Resistance Factor Design* states oversized holes are not to be used in bearing type connections.

Slip Critical Connections

Hot-dip galvanized steel slip coefficients have been misunderstood for a number of years. Newly galvanized steel tends to be very smooth, and thus has a lower slip coefficient than bare or mild steel. However, weathered galvanized steel increases the slip resistance of galvanized faying surfaces. Furthermore, over time, two galvanized faying surfaces in a friction connection will experience a lock-up phenomenon. As friction continues to build between the two zinc surfaces, they will start to bond to one another, causing the surfaces to lock-up, and increase the slip factor.

Lock Up Effect

Some time after the connection is made, galvanized joints develop a characteristic known as “lock-up.” Initially, galvanized surfaces will creep more than bare joints. However, after the first few cycles of applied stress, any creep will stop and the surfaces will start to bond to one another. The lock-up is a result of friction between the two galvanized surfaces during movement. To disassemble a locked joint requires prying of the steel surfaces. Therefore, if some initial creep is acceptable for the joint, galvanized steel can be used in the slip critical connections with the same number of bolts as bare steel designs, because over time the galvanized surface will lock-up and provide a slip coefficient equal to black surfaces.

Current industry standards by the American Institute of Steel Construction (AISC) and Research Council on Structural Connections (RCSC) list the slip coefficient of galvanized surfaces as a Class A connection (mean slip coefficient, $\mu = 0.30$). However, painting the HDG coating with zinc silicate can greatly improve friction. Power wire brushing is not permitted.

Tensioning of Galvanized Bolts

When tensioning using hot-dip galvanized fasteners, a washer should be placed underneath turning pieces in order to prevent damage to the galvanized coating. Any of the following three methods can be used to tighten hot dip galvanized bolts: calibrated wrench, direct tension indicator, or turn of nut. Additionally, some type of lubrication is advised for ease of tensioning.

Relevant Specifications

- RCSC / Bolt Council: Specification for Structural Joints Using High-Strength Bolts
- American Institute of Steel Construction, Specification for Structural Steel Buildings

Safeguarding Against Hydrogen Embrittlement

Although hydrogen embirttlement happens infrequently, the embrittlement of steel during the hot-dip galvanizing process is possible. If a steel member embrittles during galvanizing, odds are it is due to strain-age embrittlement and not hydrogen embrittlement or liquid-metal embrittlement. To greatly reduce or eliminate the potential for embrittlement of steel hot-dip galvanized after fabrication, refer to the practices and procedures defined within ASTM A143, *Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products.*

Excessive cold-working of steel prior to galvanizing is the key factor for strain-age embrittlement to develop, and the heat in the galvanizing process simply accelerates the aging of the steel making it brittle. Maximizing bend radii and performing a thermal/heat treatment of cold-worked articles prior to galvanizing effectively minimize the potential for strain-age embrittlement. Stain-age embrittlement can be observed immediately after galvanizing, as opposed to hydrogen embrittlement which is not observed until the part is under load for an extended period of time.

Hydrogen embrittlement is very rare during the galvanizing process, and typically only of concern for steels with an ultimate tensile strength greater than 150 ksi due to a tight grain structure trapping hydrogen molecules readily available from the pickling acid used in the galvanizing process. Performing mechanical cleaning instead of acid pickling, or heating after pickling to expel entrapped hydrogen, are effective means of guarding against hydrogen embrittlement for steels >150 ksi.

Liquid-metal embrittlement (LME) is the result of liquid metal which is able to contact a solid metal and initiate cracking under certain conditions (mainly temperature). It is well known that zinc cannot cause the embrittlement of steel due to the fact that people have been galvanizing steel for nearly 150 years. However, other types of metal may be susceptible to this type of embrittlement, but often require much higher temperatures than experienced in hot-dip galvanizing. As a result, this type of embrittlement is not of concern during the hot-dip galvanizing process.

Touch-Up and Repair

The touch-up and repair of hot-dip galvanized steel coatings is important to maintain uniform barrier and cathodic protection as well as ensure longevity. Although the hot-dip galvanized coating is very resistant to damage, small voids or defects in the coating can occur due to improper handling of the steel after galvanizing or from normal wear and tear.

When it comes to repairing galvanized steel in the field, there is no limitation to the size that can be repaired. The zinc coating is difficult to damage, and field fabrication that requires removal of the coating should be minimized as much as possible. As noted before, the cathodic protection of the coating will provide some protection to uncoated areas, but the best practice for longevity is to touch-up any bare areas.

The specification to follow for touch-up and repair of hot-dip galvanized steel is ASTM A780, *Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings*. This specification details how to use the three acceptable methods of touch-up as well as the required coating thickness for the repaired area.

Zinc-Based Solders

Soldering with zinc-based alloys is achieved by applying zinc alloy in either a stick or powder form. The area being repaired needs to be preheated to approximately 600F (315C). The acceptable material compositions of solders used for repair are included in the specification.

The final coating thickness for this repair must meet the specification requirement for the material category of the steel part being repaired with a maximum thickness of 4 mils (100 µm). The thickness should be measured by any of the methods in A123/A123M that are non-destructive. Zinc-based solder products closely match the surrounding zinc and blend in well with the existing coating appearance.

Hydrogen Embrittlement Case Study: Oakland Bay Bridge 2008

The San Francisco Oakland Bay Bridge (SFOBB) is connected to Pier E2 at the east side by means of 96, 3-inch diameter, galvanized ASTM A354 Grade BD (A354BD) anchor rods fabricated and installed inside the Pier E2 concrete bent cap in 2008 (2008 Rods). In early March 2013, after erection of the superstructure and load transfer was completed, the rods were pre-tensioned to 70% of their minimum specified ultimate tensile strength. A few days after tensioning was completed, 32 of the 96 anchor rods fractured. All 32 fractures occurred at or near the threaded engagements at the bottom ends of the rods. Failure of the rods ceased after the pre-tension level in the remaining rods was reduced. All of these 96 rods were abandoned and an alternative anchoring system was successfully designed and installed. Although the 2008 rods are no longer in service, their failure raised concerns about the long-term performance of the remaining A354BD rods on the bridge.

A testing program organized by the California DOT found that the 2008 rods failed as a result of environmentally-induced hydrogen embrittlement and it is not likely hydrogen was introduced by the galvanizing process to cause hydrogen embrittlement. It was also determined that there was a decrease in the hydrogen embrittlement threshold of these rods that contributed to the failures. Additionally, there was an issue with the heat treatment of one particular batch of rods which is likely the root cause for the decreased hydrogen embrittlement threshold of the affected bolts.

Overall, the results of the study indicate the rods on the bridge failed by environmentally induced hydrogen embrittlement because they were tensioned above their hydrogen embrittlement threshold while simultaneously immersed in water, which served as the source of hydrogen. The low hydrogen embrittlement threshold of the 2008 rods is likely due to rod fabrication methods, not galvanizing.

Zinc-Rich Paints

Zinc-rich paint is applied to a clean, dry steel surface by either a brush or spray. Zinc-rich paints should contain either between 65% to 69% metallic zinc by weight or greater than 92% metallic zinc by weight in dry film. Paints containing zinc dust are classified as organic or inorganic, depending on the binder they contain. Inorganic binders are particularly suitable for paints applied in touch-up applications of undamaged hot-dip galvanized areas. The coating thickness for the paint must be 50% more than the surrounding coating thickness, but not greater than 4.0 mils (100µm).

Zinc Spray (Metallizing)

Zinc spray, or metallizing, is done by melting zinc powder or zinc wire in a flame or electric arc and projecting the molten zinc droplets by air or gas onto the surface to be coated. The zinc used is nominally 99.5% pure or better. The renovated area must have a zinc coating thickness at least as thick as that required in ASTM A123/A123M for the material category.

Field Inspection

Inspection of hot-dip galvanized steel products does not end once they are accepted at the galvanizer's facility or job site. During the erection process, and once in place, the galvanized bridge components will require periodic inspection. When inspecting hot-dip galvanized steel in the field, the inspector should be aware of potential accelerated corrosion areas and aesthetic surface conditions and whether they are a concern.

When inspecting a galvanized coating in the field, the number one concern is the number of years remaining before the coating will need to be touched-up or replaced. Fortunately, estimating the remaining time to first maintenance for hot-dip galvanized coatings in atmospheric exposures is relatively simple. For a ballpark estimation, use a magnetic thickness gauge to take a coating thickness measurement and check the thickness value against the *Time to First Maintenance Chart (Figure 23).*

In addition to taking coating thickness measurements, the galvanized coating can be visually inspected for signs of accelerated corrosion in specific areas. Thickness measurements should be taken in these areas to ensure adequate zinc coating remains or if touch-up should be performed. Corrosion-prone areas to inspect further include the following:

Crevices

When corrosive elements such as water penetrate crevices, the limited air flow can create differences in potential, creating anodic and cathodic areas which can lead to corrosion. Some common areas include: overlapped areas, mated sections between fasteners, and areas where the galvanized coating is butted up against another surface such as wood, concrete, or asphalt. When possible, crevices should be avoided during the design process.

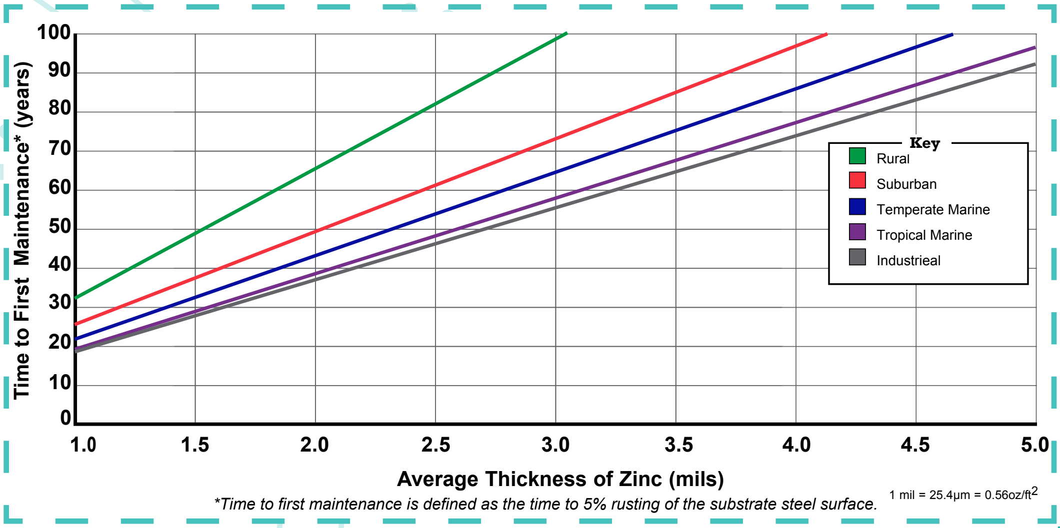


Figure 23: Time to First Maintenance

Areas Where Water Pools

Flat areas can collect water and other corrosive elements and can have higher corrosion rates than vertical surfaces. Visually observing galvanized steel's flat areas and taking coating thickness measurements will ensure adequate corrosion protection remains. Areas that collect water can be addressed by providing drain holes to prevent moisture from pooling on the surface for long periods. If drain holes do exist, inspect the drain holes of the galvanized steel for corrosion and touch-up when necessary.

Previously Touched-Up Areas

Areas of hot-dip galvanized steel previously touched-up either after the initial coating or erection can corrode more quickly than the surrounding zinc coating and should be inspected visually and tested with a magnetic thickness gauge. These areas may be touched-up when necessary using the methods noted in the touch-up and repair section of this publication to extend the service life.

During your visual inspection of galvanized steel in the field, you may observe a few common appearance issues as well. Most are surface or aesthetic conditions and not cause for concern; however, others may require attention and/or maintenance. For more information on surface conditions, refer to the AGA's publication, *Inspection of Hot-Dip Galvanized Steel Products.*

Field Repair of HDG Coatings

During field inspection, it may be determined that damage has occurred to the coating due to removal for field welding, in-service conditions, or rough handling and installation techniques. The practice for repairing the galvanized coating in the field is the same as the practice for repair at the galvanizing facility, but there are more restrictions to the allowable repair size on a new product at the galvanizing plant than for one that has been delivered to a jobsite. There is no ASTM specification which specifies a maximum allowable repair size for galvanized coatings already accepted and delivered.

Therefore, any size of repairable coating defect can be touched up in the field by any of the three approved methods described within ASTM A780, *Standard Practice for Repair of Damaged and Uncoated Areas of Hot-dip Galvanized Coatings* (i.e. zinc-based solder, zinc-rich paint, or zinc spray metallizing). The thickness requirements for the chosen repair material are specified within the associated hot-dip galvanizing specification (ASTM A123, A153, or A767) while surface preparation and application requirements are detailed within ASTM A780.

Conclusion

Each bridge offers its own unique challenges and environmental conditions, and the bridge designer must evaluate what materials are best suited for the conditions. But, as the mantel for a 100-year bridge lives continues to push forward, it is important to design bridges with sustainable, economically responsible materials. Hot-dip galvanized steel has been used in bridge designs for many years, and can be done successfully if proper design practices are considered.

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